Measurement of Top Quark Mass in Single Top Production Using the Muon Channel

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1 The Standard Model

Particle physicists have developed a theory called the Standard Model(SM), which attempts to describe all elementary particles and their interactions. The SM is a quantum field theory based on gauge symmetries. It is a very elegant theoretical framework that has succesfully passed very precise tests [1]. However, the gravitational interaction is not yet part of this framework since quantum effects of the gravitional interaction are still far from being measurable.

There are two types of elementary particles. The first are the basic building blocks of matter. The second are particles that generate interactions. The "matter" particles are fermions and fall into two classes: quarks and leptons. Both of them participate in the electromagnetic and weak, or electroweak, interactions. Quarks and leptons are distinguished from one another by the fact that quarks participate in strong interactions while leptons do not. Quarks and leptons are organized in three generations with identical properties except for mass. Each quark carries another conserved quantum number, color charge, that can have three possible values, arbitrarily denoted red, green, and blue. We cannot directly "see" color in nature because quarks are confined to colorless composite particles, called hadrons.

Particle interactions are described in terms of exchanges of "interaction" particles, bosons having spin 1. The photon mediates the electromagnetic interaction, the three weak bosons are the exchanged particles in weak interactions, and the eight gluons are the mediating bosons in the strong interaction.

In addition, there is a scalar and electrically neutral particle called the Higgs boson in the SM. The Higgs boson provides masses to the $W^{\pm}$ and Z^0 gauge bosons and to the fermions [2]. This particle has not been seen in experiments so far.

2 The Top Quark

In 1995, the discovery of the top quark was announced by DØ and CDF experiments at Fermilab. The top quark has a very short life time and a very large mass. Its life time is about 0.5×10^{-24} s, which is shorter than the charisteristic hadronization time scale. Therefore, top bound states do not have time to form [3], and therefore the top quark can be studied as a free particle. The mass of the top quark is approximately 174 GeV. It is much heavier than the next to heaviest quark, the b quark, which has a mass of about 5 GeV.
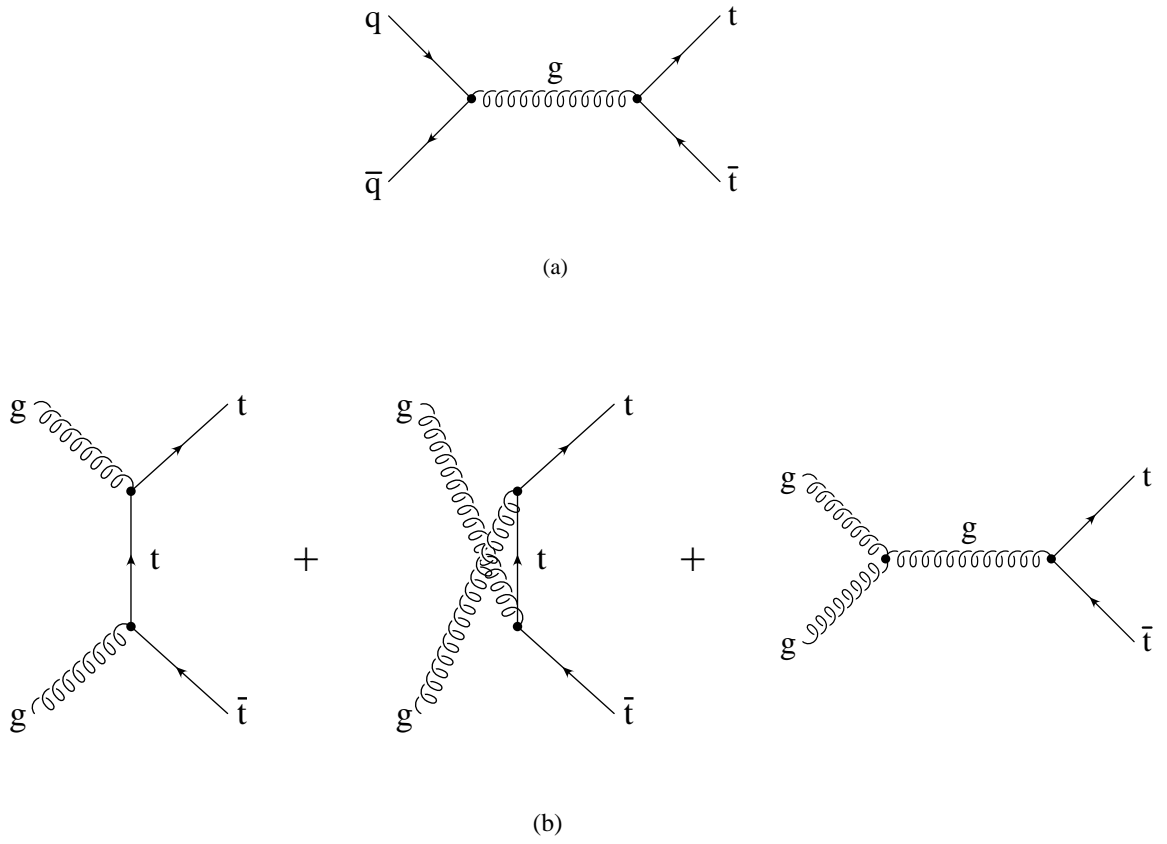
(a)

(b)

Figure 1: Top quark pair production via the strong interaction: (a) quark-antiquark annihilation; (b) gluon fusion. At the leading order (LO) there are three Feynman diagrams which contribute to the latter process.

The top quark is produced in $p\overline{p}$ collisions mostly via the strong interactions along with its antiparticle ($t\overline{t}$ pair production). At $\sqrt{s} = 1.8$ TeV (Run I) top pairs were produced 90% of the time via the quark-antiquark annihilation process ($q\overline{q}$), and the remainder of the time via gluon-gluon process (gg). In Run II, the fraction of the $q\overline{q}$ process decreases to 85%. Within the SM the top quark decays into $W + b \sim 100\%$ of the time. The W decays with the following branching ratio (BR):

W^+	$e^+\nu$	$\mu^+\nu$	$\tau^+\nu$	$u\overline{d}$	$c\overline{s}$
BR	1/9	1/9	1/9	3/9	3/9

For $t\overline{t}$ pair production the event topologies are:

- Dilepton channel ($l\nu l\nu b\overline{b}$): events for which both W's decay into e or μ. This is expected to occur with a branching ratio of 4/81, i.e., $\sim 5\%$ of the final states. Also e or μ plus τ is expected to occur in $\sim 5\%$ of $t\overline{t}$ events.

- Lepton + jets channel ($l\nu q\overline{q}b\overline{b}$): events in which one W decays into e or μ, the

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other into a quark pair. This occurs with a branching ratio of 24/81, i.e. in $\sim$ 30% of the events.

- All-jets channel($q\bar{q}q\bar{q}b\bar{b}$): events in which both W's decay into quark pairs. This occurs whth a branching ratio of 36/81, i.e. in $\sim$ 44% of the events.

DØ and CDF have observed about one hundred $t\bar{t}$ events in Run I [4]. The two experiments followed somewhat different strategies in defining their event samples. While DØ made greater use of kinematic variables to reduce backgrounds, CDF took advantage of their silicon vertex detector to identify b-quarks. The measurement of the cross section and mass by DØ and CDF are [5, 6]:

$$\sigma = 5.9 \pm 1.7 \text{ pb } m_t = 172.1 \pm 7.1 \text{ GeV (DØ)},$$

$$\sigma = 6.5^{+1.7}_{-1.4} \text{ pb } m_t = 176.0 \pm 6.5 \text{ GeV (CDF)}.$$

The combined mass from the DØ and CDF experiments is [7, 8]:

$$m_t = 174.3 \pm 5.1 \text{ GeV}.$$

Top quarks can also be produced along with a b quark through weak interactions. There are two independent modes to produce "single top" quarks as shown in Fig. 2. The first process involves an s-channel W boson, while the second process involves a t-channel W boson (W-gluon fusion). There is another process in the single top production: $gb \longrightarrow tW$. This process proceeds via a gluon-b interaction, which makes the cross section negligible at the Tevatron (0.15pb at Run I). There is no possibility of separating it from the background.

The final state of the W-gluon fusion has a W boson, a forward light quark jet, and two central b jets, one with high p_T and the other with low p_T. Following the decay of the top quark, the s-channel process contains a W boson and two b quarks that hadronize into two central jets with high p_T.

There are several background processes which must be considered in order to establish whether the signal can be observed.

- Top Quark Pair Production
  $t\bar{t} \longrightarrow e\nu q\bar{q}b\bar{b}$ or $\mu\nu q\bar{q}b\bar{b}$

- W + Jets Events

  $Wb\bar{b} \longrightarrow$ e$\nu b\bar{b}$ or $\mu\nu b\bar{b}$

  $Wjj \longrightarrow$ eνjj or $\mu\nu jj$

- WW and WZ Pairs

  $WW \longrightarrow$ e$\nu u\bar{d}$ or $\mu\nu u\bar{d}$

  $WZ \longrightarrow$ e$\nu b\bar{b}$ or $\mu\nu b\bar{b}$

- QCD Multijet Events

Because the W$b\bar{b}$ process has the same final states as our signals, it is called an "irreducible" background. In order to separate this background from the signals we have to study details of the kinematics carefully.
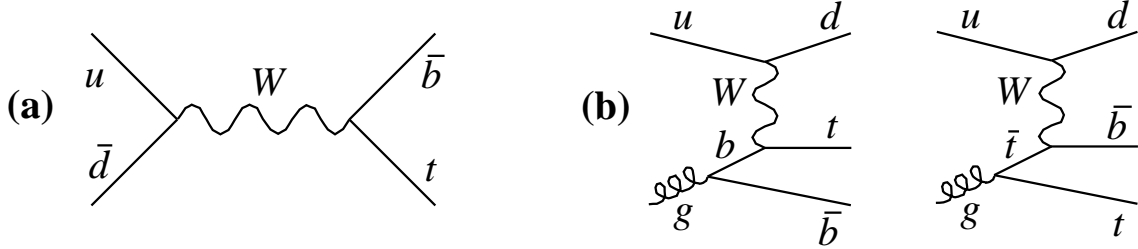

Figure 2: Two dominant processes for single top quark production at the Tevatron: (a) s-channel process. Signal is $W + b + \bar{b}$; (b) t-channel process. Signal is $W + b + \bar{b} + q$
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3 The DØ Detector for Run II

Since the end of Run I the DØ collider detector at the Fermilab Tevatron has been upgraded for Run II. The expection is that Run IIa will provide an integrated luminosity of 2fb^{-1}, about 20 times that of Run I. Also the center-of-mass energy of $p\bar{p}$ collisions has increased from 1.8 TeV to 1.96 TeV. With these upgrades the DØ experiment will have considerable discovery potential for new phenomena as well as the ability to make more precise studies of the SM.

The DØ detector has 3 subdetector systems. These are the tracking detectors, calorimeters, and muon detectors. The tracking detectors consist of the silicon microstrip tracker (SMT) and the central fiber tracker (CFT). Both tracking detectors are designed to provide adequate momentum resolution for charged particles up to a pseudorapidity (η = -lntan($\theta/2$)) = 3, excellent impact parameter resolution for b-tagging and fast track triggering.

The SMT has 6 barrels along the beam direction with 4 layers (double/single sided) silicon strip detectors each, 12 disks (double sided) in between and at the end of the barrels, as well as 4 disks (single sided) for tracking in the very forward region. The CFT is installed outside the SMT for extended central tracking. It has 8 double layers of scintillating fibers located at 30cm < r < 53cm. The light signals are transmitted via clear waveguide fibers to Visible Light Photon Counters (VLPCs), situated below the DØ detector inside a cryostat at a temperature of 9K. The SMT and CFT are surrounded by a superconducting solenoid providing a magnetic field of 2T.

A calorimeter is a device to measure particle energies. The DØ calorimeter uses uranium and iron absorber bathed in liquid argon. The absorber causes particles to interact and lose energy and the ionization in the argon, which is proportional to the sampled energy, gives an electrical signal that we can measure. The calorimeter is divided into three parts, the central calorimeter and the two end calorimeters, and covers the pseudorapidity range $| \eta | < 4.2$. Longitudinally, that is transversely to the beam, the calorimeter is segmented into an electromagnetic (EM) section and a hadronic section.

The purpose of the muon system is to identify and measure the momentum of muons that penetrate the calorimeters. The muon system consists of central and forward regions with three layers of scintillators and drift tubes, one inside and two outside the magnetized iron toroids.

4   Motivation for a Measurement of the Top Quark Mass in Single Top Production

The top quarks are mostly pair-produced via the strong interaction through an intermediate gluon at the Tevatron $p\overline{p}$ collider. In the SM a second production mode is predicted to exist, where top quarks are created singly through an electroweak Wtb vertex. We have a good opportunity to prove the existence of the single top production and to study Wtb vertex.

The top quark mass was measured in $t\bar{t}$ pair production using data collected in Run I. Run II promises a much larger data set (about 100 times larger) than that of Run I. Such a data set could yield a substantially smaller uncertainty in our knowledge of the top quark mass. In order to achieve that goal, it is necessary to measure the top mass in as many channels as possible. Moreover, it is necessary to check that the top mass measured in a weak interaction process is the same as that measured in a strong interaction process. If we obtain very different values, it might be an indication of new physics.

Understanding single top production will also be very helpful for the Higgs search at the Tevatron because the WH channel has an identical final state with kinematics very similar to the s-channel top production.

5   The Search for Single Top Quark Production in Run I

The DØ collaboration collected about 100pb^{-1} of data from 1992-1995 at a $p\bar{p}$ center of mass energy of 1.8 TeV. The predicted cross section of the W-gluon fusion is 1.70±0.24 pb and that of s-channel is 0.73±0.10 pb. So there could have been about 66 s-channel and 153 t-channel single top quark events during Run I [10, 11].

During, Run I, DØ searched for s-channel and t-channel production modes, with decay of the W boson into $e\nu$ or $\mu\nu$, and identification of a b jet via a tagging muon. For the measurement in the electron channel, trigger requirements included an electro-magnetic (EM) energy cluster in the calorimeter, a jet, and missing transverse energy ($\not{E}_T$). The efficiency of the trigger was 90-93%. In the muon channel, triggers required $\not{E}_T$ or a muon within a jet. The combined efficiency of these triggers was 96-99%. Each of the samples contained approximately one million events.

The electron candidate was defined by a set of identification criteria, which a jet candidate had to fail. In addition, a jet candidate had to satisfy certain jet-specific criteria, such as a minimum energy fraction in the hadronic calorimeter. An electron had to have transverse energy $E_T > 20$ GeV, and be within the optimal region of the calorimeters with detector pseudorapidity $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. The efficiency of the combined electron identification was $\approx 60\%$. The jet with the highest transverse energy was required to have $E_T > 15$ GeV and $|\eta| < 3.0$. The second jet had to have $E_T > 10$ GeV and $|\eta| < 4.0$. Other jets in the event were counted if they had $E_T > 5$ GeV and $|\eta| < 4.0$.

Muons had to be within the central region, that is $\mid \eta \mid$ < 1.7. A muon is called isolated if $\Delta\mathrm{R}(\mu,\mathrm{jet})$ ($\Delta\mathrm{R} = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, where ϕ is the azimuthal angle) $\geq$ 0.5 for all jets with E_T > 5GeV. An isolated muon must have p_T > 20 GeV and is attributed to the decay of a W boson. A tagging muon was defined by $\Delta\mathrm{R}(\mu,\mathrm{jet})$ < 0.5 and p_T > 4 GeV. It is attributed to the semileptonic decay of a b hadron in a jet, and thus identifies a b jet. The probability of identifying at least one tagging muon in a single top quark event was 6 - 11%. The efficiency of the combined muon identification requirements was $\approx$ 44% for isolated muons.

Because W decays into an electron or a muon and a corresponding neutrino, $\not{\!E}_T$ > 15 GeV was required as a signal of a neutrino in a signal event. The number of jets is 2 - 4 and that of isolated leptons is one. In order to remove the contamination from cosmic rays, events where the isolated muon and tagging muon are back-to-back were rejected; $\Delta\mathrm{R}(\mathrm{isol}\mu,\mathrm{tag}\mu)$ < 2.4 rad.

Table 1: Signal acceptances (as percentages of the total cross sections), and numbers of events expected to remain after application of all selection criteria.

	Electron Channel	Muon Channel
	Acceptances	
tb	$(0.255 \pm 0.022)\%$	$(0.112 \pm 0.011)\%$
tqb	$(0.168 \pm 0.015)\%$	$(0.083 \pm 0.008)\%$
	Numbers of Events	
tb	0.18 ± 0.03	0.08 ± 0.01
tqb	0.28 ± 0.05	0.13 ± 0.03
W+jets	5.59 ± 0.64	1.12 ± 0.17
QCD	5.92 ± 0.58	0.40 ± 0.09
$t\bar{t}$	1.14 ± 0.35	0.45 ± 0.14
Total Bkgd	12.65 ± 0.93	1.97 ± 0.24
Data	12	5

In addition to these selections, the following requirements were applied to obtain the best significance, defined as signal over square root of background, based on Monte Carlo studies [13].

- Electron Channel

  $\mathrm{E}_T(\mathrm{jet1}) + \mathrm{E}_T(\mathrm{jet2}) + \mathrm{E}_T(e) + \not{\!E}_T$ > 125GeV

  $\mathrm{E}_T(\mathrm{jet3}) + 5 \times \mathrm{E}_T(\mathrm{jet4})$ < 47GeV

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$E_T(jet1) + 4 \times \not{E}_T > 155\text{GeV}$

- Muon Channel

  $E_T(jet1) + E_T(jet2) + E_T(jet3) + E_T(jet4) > 70\text{GeV}$

  $E_T(jet3) + 5 \times E_T(jet4) < 47\text{GeV}$

After all requirements, the number of events expected for signals and backgrounds are shown in Table I. The DØ collaboration found no evidence of single top quark production in Run I. The collaboration set 95% confidence level upper limits on the cross sections for s-channel and t-channel. Recently DØ calculated updated upper limits with neural networks [9]:

$\sigma(tb) < 17\text{pb}$, $\sigma(tqb) < 22\text{pb}$.

6   Plan

In this work our goal is to make as precise a measurement as possible of the top quark mass in the single top production mode using the muon channel. The disadvantage of the muon channel is its relatively low branching ratio ($\sim$11%). The channel has, however, fewer backgrounds and is easier to detect. In order to achieve our goal we must have enough single top events for reconstructing the mass. However, we do not yet have evidence for the existence of single top production. Therefore, our analysis will start by estimating how much integrated luminosity will be needed to make our task feasible.

The most serious problem we face is that separation of signals from backgrounds in single top production is much harder than for $t\bar{t}$ pair production. The reason is that the jet multiplicity of a single top quark event is typically less than that of a $t\bar{t}$ event and so QCD multijet and Wjj backgrounds are much higher. In order to find an optimal strategy to search for single top quark, a detailed background study is needed.

In Run II the expected cross secions for the signals are expected to increase approximately 20% and 40% for tb and tqb, respectively ($\sigma(tb) = 0.88\pm0.05$pb, $\sigma(tqb) = 2.44\pm0.12$pb) [10, 11]. Backgrounds will also increase by a similar order. We anticipate the b-tagging efficiency to reach about 60% and suppose the trigger efficiency to be the same as in Run I. We will create the MC simulations using CompHEP [12], for the complete set of the single top production and background processes. Whenever possible we shall check our models with data. Selection criteria will be developed to separate

signals from backgrounds starting with those developed in Run I. After applying all criteria and making our estimation, a preliminary result will be presented.

According to a CDF estimation, the expected number of events are [14]:

Run I	Events	Run II	Events
Signal	2.8±0.5	Signal	140
$t\bar{t}$ background	7.1±2.1	$t\bar{t}$ background	340
All non-top background	27±5	All non-top background	1040

This result corresponds to S/$\sqrt{B}$ = 0.54σ (Run I) and S/$\sqrt{B}$ = 4.34σ (Run II). CDF supposes that the acceptances of leptons would increase by 33% (electron), 12% (muon) and that b-tagging efficiency would increase by 50%. In addition to improving efficiencies of accepting signals and rejecting backgrounds, more precise particle identification strategies are essential to increase the signal to background ratio. Therefore, in order to perform our analysis successfully, we must fully understand particle identification techniques, and appropriate statistical tactics to separate signals from backgrounds.

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